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SERT II HOLLOW CATHODE MULTIPLE RESTARTS IN SPACE

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Abstract

Future missions, both station keeping and primary electric propulsion, will require multiple thruster restarts after periods of inactivity from a few hours to over one year. Although not a part of the original SERT II (Space Electric Rocket Test) flight objective, the opportunity to demonstrate multiple cathode restarts in space became available following completion of thruster running. Both neutralizer and main cathodes of each flight thruster have been restarted repeatedly following storage periods up to 490 days. No deterioration of cathode heaters has been noted nor has any change been required in starting voltages or currents.

Introduction

The SERT II thruster design, frozen in 1967, called for long operating life (6 months) and the capability to restart after ground testing or space running without refurbishment of any component.[1,2] These requirements were necessary to satisfy various mission requirements proposed at that time. Although the exact number of thruster restarts were not specified for the SERT II thruster, only ten or twenty restarts were assumed necessary. It was important that the thruster start after long periods of operation rather than demonstrate a great number of multiple restarts. Present missions, however, require many restarts. For example, a 5-year geosynchronous satellite would require station keeping thrusters to be restarted nearly 2000 times, or a satellite orbit raising primary propulsion thruster might be restarted several hundred times following eclipse periods.

To demonstrate cathode starting technology in space, it became desirable to reactivate the SERT II spacecraft. (The SERT II spacecraft had been turned off earlier following failure to clear a high-voltage short existing in each thruster.) Although the SERT II spacecraft and thrusters were not designed to perform a multiple cathode restart test program, it is possible to manually command the cathodes to light and then turn them off. Approximately 30 to 40 lighting attempts per month can be accomplished within present program priorities. A period until spring of 1974 is available for this purpose before the solar array sunline becomes too shallow to provide operating power.

In addition to performing multiple cathode restarts, the SERT II spacecraft reactivation can also demonstrate as another purpose that hollow cathodes can be restarted after long (~1 yr) periods of space storage. Long thruster storage periods are generally proposed both to match mission power profiles and for redundant, stored, auxiliary and prime thrusters.

Restarting should be no problem, if the design and operation of the hollow cathode is done correctly. The loss rate of BaO from the SERT II cathode insert was very low and the 10 mg of BaO added to the insert can be many times more than is used. However, high operating insert temperature or high discharge voltage may cause excessive evaporation or sputtering, respectively, and exhaust the supply of BaO in several hundred hours or less.[3] Hollow cathode starting reliability is the subject of several papers at this and previous conferences.[4-7] A high voltage spark starting technique offers excellent promise as a prime starting method or as a backup to the conventional BaO activation method.[4,8]

This paper documents the multiple restarts of the SERT II thruster cathode made since May 1973 and compares these restarts with those made both earlier in the flight and during preflight ground testing. The data cut-off time of this writing was July 17, 1973.

SERT II Spacecraft and Thrusters

The SERT II spacecraft was launched February 3, 1970 into a 1000-km altitude, polar, sun-synchronous orbit. A description of the spacecraft and its two 15-cm diameter mercury bombardment ion thrusters may be found in references 9 and 10, respectively. Orbit precession since the time of launch has changed the solar array sun line from an initial value of about 90° to a present value of approximately 30°. Also, the spacecraft now passes through the Earth's shadow every orbit. As the on board battery is dead and the only source of electrical power is the solar array, all operations must be conducted during the approximate 70 min sunlight period per orbit. By mid-1974 the continued orbit precession will have reduced the sunline to such a shallow angle that insufficient power will be available during the sunlight period to either housekeep the spacecraft or turn on the thrusters.

The present level of spacecraft power permits simultaneous preheat and full cathode discharge operation of both thrusters. Ion beam production, the major thruster power load, is precluded both by the available power level and the high voltage short in each thruster. Continuous cathode operation is precluded by the 35 min eclipse period per orbit. Cathode restarts, however, can be attempted in real time during an approximate 15-min pass period of direct communication with a given ground station.

Cathodes and Starting Procedure

Figures 1, 2, and 3 show, respectively, the assembly details of the main cathode, the neutralizer cathode, and cathode heater. The cathode heater and insert design were identical for both the main and neutralizer cathodes. The original SERT II starting procedure was to preheat the thruster and cathodes by turning on all heaters (except the main vaporizer) and discharge voltages for 90 min. In this time the cathodes reached starting temperatures and the thruster body was warm enough to prevent condensation of mercury propellant vapor. The neutralizer assembly, having a

small thermal mass, heated more quickly and started its discharge in the first few minutes. The main discharge was started (following the 90-min preheat) by turning on the main vaporizer. The SERT II flight thrusters have always started reliably using this original starting procedure.

Due to the presently limited time available for starting, a "quick start" procedure is used to attempt lighting of the main cathode. The neutralizer cathode lighting, which only requires several minutes to light, is still done by the original procedure. "Quick starts" of the main cathode may be done in 6 to 20 min even though the propellant flow control may be unstable due to partial propellant condensation. Because of time for the ground station to acquire the spacecraft signal and send commands, and uncertainties in length of pass period, the actual time of cathode heating is limited to 10 to 12 min. This time period does not impact starting of the neutralizer cathode which conducts heat to a small thermal mass, but may preclude main cathode starting within the limits of a ground station. In a few instances pass schedules afford the opportunity for consecutive spacecraft coverage over two ground stations. Exercising this opportunity permits 20 to 25 min of thruster preheat before attempting to start the main cathode, and insures starting of the main cathode.

Data Accuracy and Analysis

Cathode starting reliability can be inferred from time to light the cathodes (using a constant starting procedure) and from any change in cathode heater resistance. These data, when received from the SERT II spacecraft, are both commutated (once per min) and quantized (0 to 61 "counts"). Indicators of cathode lighting are step changes in the discharge or heater supplies. The uncertainty in determining the time of cathode lighting is 0.03 to 0.6 min depending on location of the indicator within the commutation cycle. The possible error due to data quantizing and calibration is ±3 percent expressed as a root-sum-square.

The time of cathode lighting is always taken from the start of preheat for the neutralizer cathode. For a "quick start" of the main cathode the time is also taken from the preheat start, but for a long (normal) preheat the start time is computed from the turn on of the main vaporizer. (Preheat turns on both cathode tip heaters, both keeper voltages, main anode voltage, and neutralizer vaporizer. The main cathode start for a long preheat period follows turn on of the main vaporizer. During a "quick start" attempt the main vaporizer is commanded on about 10 seconds following the preheat command.)

Summary of Cathode History

The neutralizer cathodes were fabricated in July 1969 (5 months before first use) and the main cathodes were fabricated in November 1969 (one month before use). Both thrusters were first operated on the ground in a series of four separate tests with exposures to atmosphere between each test during December 1969. Each test included only one preheat and start cycle with the exception of the final test with thruster 2. During this test and for nonrelated thruster problems, five preheat and start cycles were done. The total hours of cathode operation during ground testing was 83 hr (thruster 1) and 91 hr (thruster 2).

Thruster 1 was turned on in space February 13, 1970 and endurance tested for 3763 hr. Two restarts were made during this period, one at 508 hr following a lunar eclipse of the sun and the other at 2283 hr following an automatic thruster shutdown due to a temporary high voltage overload. Thruster 2 was turned on in space February 10, 1970, operated for a few hours to verify correct operation, and then stored for future use. Following the 3763 hr test of thruster 1, thruster 2 was turned on again on July 24, 1970 after 164 days storage and endurance tested for 2011 hr. One restart was done on thruster 2 after 936 hr following a lunar eclipse of the sun.

During the period of October 1970 to January 1972 each thruster was started a number of times in attempts to clear its high voltage short. Both thrusters were then stored from January 21, 1972 to May 25, 1973 (490 days). From May 25, 1973 to July 17, 1973 (time of this writing) both thrusters were restarted 50 times to demonstrate restart capability. Figure 4 chronologically shows the number of cathode restarts, storage time between, and total hours of running. All starts prior to October 1970 were made following a minimum of 90 min preheat. Starts since October 1970 have been made with various preheat times between 5 and 90 min.

Flight Thruster Cathode Starting

At the time of this writing all four cathodes (main and neutralizer cathode of two flight thrusters) continue to light and function normally using the original starting currents, voltages, and preheat times. This record includes 82 preheats of thruster 1 and 126 preheats of thruster 2. Within the abbreviated preheat period imposed by the time limit of coverage by a ground station, the main cathode of thruster 2 has not lighted six times in the last fifty attempts. Main cathode 2 has always lighted, however, following 20 min or more of preheat. All three other cathodes have lighted on each attempt.

Figures 5 and 6 show for thrusters 1 and 2, respectively, the time to start each cathode versus the start or preheat number. All of the recent (last 50 start attempts) are plotted and representative starts are plotted for the period from the initial light (late 1969) to January 21, 1972 (start of 490 day storage period). The time between start numbers can be determined with the help of figure 4. The data error bars of figures 5 and 6 are uncertainty times resulting from the commutated form of the returned spacecraft data.

No definite trend of start time has developed over the last 50 start attempts on any of the four cathodes. The starting times range between 5 to 12 min (fig. 5 and 6) and depend on component thermal time constants coupled with initial temperatures. The SERT II project philosophy precluded having many temperature measurements on the flight thrusters. The flight thruster initial temperature can best be inferred by the temperature of the neutralizer reservoir. The start times "early" in spacecraft life (start numbers

5 to 20 for thruster 1 and 10 to 67 for thruster 2) are shorter corresponding to a higher initial temperature of the thrusters. This temperature was 78° to 97° C in "early" life and is 22° to 27° C presently (last 50 attempts) due to partial orbit eclipse. Both main cathodes, when preheated for 20 min or more, had a very short and consistent starting time of two minutes or less. These short starts can be seen on figures 5 and 6 for "early" life start attempts as well as those done recently, i.e., start numbers 47 and 77 for thruster 1, and 90 and 120 for thruster 2. The short starting time procedure is the strongest evidence that indicates that the main cathodes are continuing to light normally and consistently. This procedure holds true after 3881 hr (total operation time) with 82 starts and 2162 hr with 126 starts for thrusters 1 and 2, respectively. Presently there there is no known reason for a wider (5 to 12 min, fig. 3) "quick" starting time range on main cathode 2 compared to the narrower range of the other three cathodes.

The space storage of SERT II hollow cathode affects their operation in no noticeable way. This is true for storage periods of 490 days as well as shorter periods of 50 to 150 days. (Storage periods can be seen on fig. 4.) Consistent neutralizer starting times before/after storage, start numbers 32/32, and 76/77 for thrusters 1 and 2, respectively, can be seen on figures 5 and 6 for the 490 day storage. As the main influence on the SERT II-type cathode starting can one of chemical degradation of the insert active material, the absence of any degrading chemical constituents in space should afford space storage adequate for all potential missions.

Table 1 lists representative values of heater currents and voltages, cathode starting times, neutralizer reservoir temperature, and total cathode on time. The starting time tolerance values of table 1 are a result of the commutation of the spacecraft data, and appear on figures 5 and 6 as error bars. The reliability of the heaters can be inferred from the consistency of the currents, voltages, and resistances (ratio of heating voltage-to-current). The hot resistance of each flame-sprayed Al_2O_3 cathode tip heater (fig. 3) is about 3 ohms.(2) The values of table 1 include a nichrome heater in series with each cathode tip. The main cathode has a nichrome isolator heater (fig. 1) of 2.5 ohms, thruster 1, and 2.6 ohms, thruster 2. The neutralizer cathodes have nichrome vaporizer heaters of 0.67 ohm values for each thruster. The main vaporizer heater is also a nichrome heater in a tantalum sheath. The currents and voltages of table 1 were the maximum value that each reached before being cut back by the control logic after cathode lighting. Source variation in this maximum value results from different times that the heater was on before it was cut back, and other variation occurs due to the quantizing (±3%) of the spacecraft data. Within these variables the authors interpret the heater values to indicate no degradation of any heater to date.

SERT II space restart attempts will continue at the rate of two per day until insufficient power exists from the solar array to perform attempts or other program priorities dictate discontinuation of this effort. Estimated propellant remains in the tanks to perform 1500 or more restarts.

Ground Testing of Cathodes

Each flight thruster was qualified in ground testing before launch. Thruster 1 was started four times on the ground and thruster 2, nine times. Both thrusters were exposed to atmosphere four times between tests. The first time that a cathode is lighted, a longer period is needed for conversion of the carbonate in the insert and activation of the tip. As seen in table 1, start number 1 for each thruster required the longest starting time for the neutralizer cathode. The initial short time of the main cathode was short because the 90 min thruster preheat cycle allows more than adequate time for cathode activation processes to occur.

Since no means were provided to measure cathode temperatures on the flight thrusters, separate ground tests were conducted in bell jars to measure cathode temperatures. These tests were done to provide estimates of cathode operation temperatures for the design of future thruster cathodes. The cathode construction and heaters were identical with flight hardware and the cathode assemblies, mounted in a vacuum bell jar, closely simulated the thermal environment of an actual thruster. Figure 7 is a plot of equilibrium preheat temperatures of SERT II prototype cathodes. The cathode tip temperature was measured by a calibrated optical pyrometer with corrections made for spectral emissivity and window transmission losses. The main cathode is hotter than the neutralizer because of the nearness to and quantity of heat applied by the isolator heater. Figure 7 indicates that the cathode tip temperatures at flight preheat currents of 2.78 to 2.97 A may have reached 1250° to 1350° C. The time constant of the tip heater, however, is 3 min, so that in 5 to 6 min of heating the tip, as for many of the last 50 neutralizer starts, the temperature is probably 100° C lower than the equilibrium values of figure 7. After the cathode lights the tip heater power is reduced, resulting in a neutralizer cathode tip temperature of approximately 1100° C.

To estimate the main cathode tip temperature while operating a thruster, a complete prototype SERT II thruster was placed in a bell jar.(11) The main discharge was turned on but no beam current was extracted. The main cathode tip temperature was measured by a calibrated optical pyrometer. The temperature data, corrected for spectral emissivity and window transmission, is plotted in figure 8 for a range of discharge emission and cathode heater powers. The curve for cathode heater current of 1.5 A, the value of the cut-back heater current for the flight thrusters, indicates that the main cathode tip temperature was about 1250° C for steady-state discharge operation at 2 A cathode emission. The back portion of the insert temperature, however, should be at least 100° C cooler than the tip because 80 percent of the cathode heat is released at the cathode tip from self-heating by the discharge. Only 20 percent (6.1 W) is supplied by the heater which is over the insert. These values were deduced by thermal analysis and cross comparing the power and temperatures of figures 4 and 5.

Discussion of Cathode Life

The results of this paper indicate that hollow cathodes can be designed and operated to meet space thruster mission requirements of thousands of hours operation and hundreds of restarts. Future cathode design operation should be equivalent to or better than the SERT II conditions listed herein, i.e., preheat temperatures of 1150° to 1300° C and operating temperatures equal to or less than this range. The potential life limiting processes in hollow cathodes of the SERT II design are (1) erosion of the tip, (2) exhaustion of the insert active material, and (3) heater failure.

Erosion of the tip has been reduced to a negligible level as evidenced by observations following ground life tests of the SERT II thrusters[9,12] and by technology life tests of 30-cm and 5-cm diameter thruster cathodes.[13,14]

The cathode inserts were removed and analyzed for BaO and SrO content following the conclusion of the SERT II thruster ground life tests T and M.[9] In addition, a new cathode insert was analyzed at the same time by the identical technique. The results of the analysis indicated that the cathode inserts, operated 5412 and 6787 hr, respectively, in life tests T and M, still contained a major portion of the BaO and SrO found in a new insert.

Exhaustion of insert active material or heater failure problems have been nonexistent in the SERT II flight thrusters or ground life tests to date. This should continue to be so in future thrusters if correct operating temperatures and heater fabrication procedures are followed.

Although the SERT II cathode insert temperature was not measured directly, it was estimated from the bell jar measurements above to be 1100° to 1150° C for steady-state operation. The evaporation life of the insert active material can be calculated by knowing the initial quantity of active material, its vapor pressure during operation, and the flow geometry for escape of the active material. The new SERT II cathode inserts contained 10 mg of $BaCO_3$-$SrCO_3$ coating (Radio Chemical R-500, J. T. Baker Co.). The vapor pressure of BaO at 1100° C is 4×10^{-6} torr and the major flow of BaO vapor will be back up the cathode tube, 0.24-cm inside diameter. (Flow conduction calculations indicate that only 10 percent of the BaO will pass out the cathode orifice.) The calculated time for the BaO contained in 10 mg of R-500 to evaporate from the insert and flow away is 14 900 hr. Depletion of SrO is not of concern because its vapor pressure is 3 orders of magnitude lower than that of BaO. Therefore, a SERT II insert containing 10 mg of R-500 and operating at no more than 1100° C should not exhaust its supply of active material in 14 900 hr of continuous operation. Enough active material must also be included for preheat times. If 2000 preheats were necessary at 1300° C (possible SERT II preheat temperature) for 6 min each, the calculated evaporation loss would be equivalent to 9000 hr of continuous heating at 1100° C. The SERT II cathodes were designed for 10 000 hr steady state operation and perhaps only 50 restarts. Obviously if future thrusters must restart (preheat) 2000 times, a lower temperature or shorter preheat periods would be necessary with the same quantity of R-500 on the insert. An excellent way to augment or insure cathode starting in future thrusters is to use a spark starting technique of reference 4 or 8 in addition to the chemical activation afforded by an insert. Spark starting erodes have been designed into a flight prototype 8-cm thruster (SIT-8).

Concluding Remarks

The SERT II flight thrusters have been operated 3881 hr and 2162 hr with 82 and 162 starts, respectively. A cathode restart program is continuing on the flight thrusters. Prototype thrusters have operated 5412 and 6832 hr in ground life tests without failure. These data indicate that with proper design and operation it is possible to operate and restart a hollow cathode thruster for long times and many restarts successfully. The cathode active material on the insert, has shown no tendency to deplete in cathode starting tests with the SERT II cathodes. It is recommended that the insert design temperature be kept low (<1100° C) for long life rather than to increase the initial supply of active material. With such a low insert temperature design, hollow cathodes should be capable of 10 000 hr operation and 2000 restarts, depending on thermochemical activation for restart. A newly-conceived spark starting technique offers excellent alternative to thermochemical activation starting.

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Table 1. Representative heater values[c] and cathode starting times

Thruster	Start number	Date	Main vaporizer			Main cathode			Neut. cathode			Cathode start time		Total cathode on time,[d] hr	Neutralizer reservoir temperature, °C
			I2, A	V2, V	V2/I2, Ω	I3, A	V3, V	V3/I3, Ω	I7, A	V7, V	V7/I7, Ω	Neutralizer cathode, min	Main cathode, min		
1	1	12/9/69	2.80	(a)	(a)	2.80	>15	>5.3	2.78	(a)	(a)	$8.5^{+0.0}_{-0.0}$	$0.3^{+0.0}_{-0.0}$	----	(a)
	4	12/28/69	2.81	(a)	(a)	2.92	15.7	5.4	2.79	9.9	3.6	$6.2^{+0.0}_{-0.0}$	$0.4^{+0.0}_{-0.0}$	----	(a)
	5	2/14/70	2.81	2.74	0.98	2.88	15.7	5.5	2.90	10.3	3.6	$3.3^{+0.4}_{-0.6}$	$0.3^{+0.7}_{-0.0}$	0	78
	6	3/8/70	2.89	(a)	(a)	2.88	15.3	5.3	2.90	10.6	3.7	$4.2^{+0.1}_{-0.6}$	$0.3^{+0.7}_{-0.0}$	508	83
	7	5/21/70	(a)	2.67	(a)	2.88	15.3	5.3	2.90	10.8	3.7	$4.3^{+0.4}_{-0.6}$	$0.7^{+0.3}_{-0.1}$	2283	78
	8	7/23/70	2.89	2.67	0.93	2.88	15.3	5.3	2.90	10.6	3.7	$4.3^{+0.4}_{-0.6}$	$1.0^{+0.3}_{-0.3}$	3763	18
	14	10/26/70	2.89	2.60	.90	2.88	14.1	4.9	2.90	10.8	3.7	$4.2^{+0.4}_{-0.6}$	[b]$4.4^{+0.7}_{-0.3}$	3794	47
	20	2/11/71	2.89	2.67	.93	2.88	15.7	5.5	2.90	10.3	3.6	$4.2^{+0.0}_{-0.6}$	$0.3^{+0.7}_{-0.1}$	3835	83
	32	1/21/72	(a)	(a)	(a)	2.88	15.7	5.5	2.79	10.1	3.6	$6.2^{+0.0}_{-0.6}$	(a)	3868	29
	33	5/25/73	2.81	2.74	0.97	2.82	15.3	5.4	2.90	10.6	3.7	$6.6^{+0.4}_{-0.4}$	[b]$6.4^{+0.4}_{-0.3}$	3869	(a)
	53	6/20/73	2.89	2.67	0.93	2.82	15.3	5.4	2.90	10.8	3.7	$5.8^{+0.1}_{-0.6}$	[b]$6.9^{+0.1}_{-0.3}$	3873	(a)
	82	7/16/73	2.89	2.74	0.95	2.82	15.3	5.4	2.90	10.8	3.7	$6.0^{+0.0}_{-0.4}$	[b]$8.0^{+0.0}_{-0.4}$	3881	(a)
2	1	11/29/69	2.89	(a)	(a)	2.78	>15	>5.4	2.94	(a)	(a)	$10.0^{+0.0}_{-0.0}$	$1.0^{+0.0}_{-0.0}$	----	(a)
	4	12/21/69	2.90	(a)	(a)	2.77	16.0	5.8	2.86	(a)	(a)	$6.3^{+0.0}_{-0.0}$	$1.0^{+0.0}_{-0.0}$	----	(a)
	10	2/11/70	2.88	2.77	0.96	2.86	16.0	5.6	2.97	10.2	3.4	$3.2^{+0.2}_{-0.6}$	$0.4^{+0.9}_{-0.3}$	0	97
	11	7/24/70	2.97	2.70	0.91	2.86	16.0	5.6	2.97	10.2	3.4	$3.2^{+0.1}_{-0.4}$	$0.9^{+0.9}_{-0.4}$	38	97
	12	9/2/70	2.97	2.70	.91	2.81	15.6	5.6	2.97	10.4	3.5	$3.7^{+0.1}_{-0.6}$	$0.9^{+0.9}_{-0.4}$	934	65
	15	10/20/70	2.97	2.70	.91	2.81	15.6	5.6	2.97	10.4	3.5	$2.8^{+0.1}_{-0.6}$	$0.9^{+0.9}_{-0.4}$	2011	73
	33	10/30/70	2.97	2.70	.91	2.81	15.6	5.6	2.97	10.4	3.5	$3.1^{+0.0}_{-0.6}$	$0.5^{+0.9}_{-0.0}$	2053	73
	53	11/13/70	2.97	2.70	.91	2.81	15.6	5.6	2.97	10.4	3.5	$2.8^{+0.1}_{-0.6}$	$0.9^{+0.9}_{-0.4}$	2094	69
	67	2/26/71	2.97	2.70	.91	2.86	16.0	5.6	2.97	10.4	3.5	$2.7^{+0.1}_{-0.6}$	$0.4^{+0.9}_{-0.3}$	2126	115
	76	1/21/72	(a)	(a)	(a)	2.86	16.0	5.6	2.97	10.4	3.5	$5.3^{+0.3}_{-0.6}$	(a)	2149	33
	77	5/25/73	2.97	2.77	0.93	2.81	15.6	5.6	2.97	10.4	3.5	$5.3^{+0.4}_{-0.6}$	[b]$7.9^{+0.4}_{-0.3}$	2150	27
	97	6/20/73	2.97	2.70	.91	2.81	16.0	5.6	2.97	10.4	3.5	$5.0^{+0.1}_{-0.4}$	[b]$9.9^{+0.1}_{-0.4}$	2154	23
	126	7/17/73	2.97	2.70	.91	2.81	16.0	5.6	2.97	10.4	3.5	$5.2^{+0.0}_{-0.4}$	[b]$8.2^{+0.0}_{-0.4}$	2162	22

[a]Data not taken or unavailable.

[b]No preheat used.

[c]Quantizing and calibration error, ±3%, root-sum-square.

[d]Includes heating time in space only; ground time, thruster 1 - 83 hr, thruster 2 - 91 hr.

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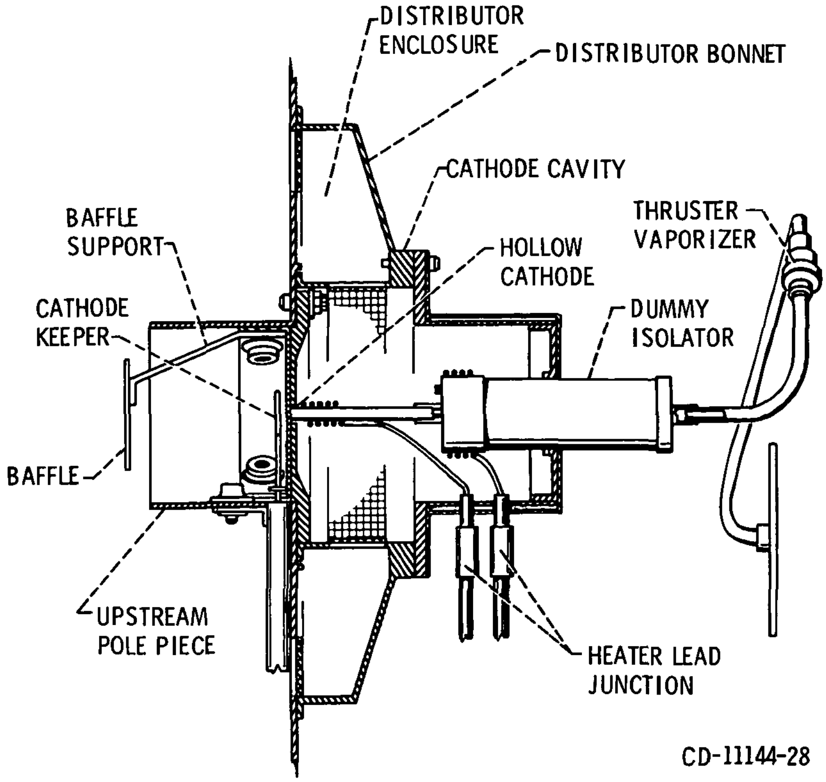

Figure 1. - Cross-sectional view of main cathode assembly.

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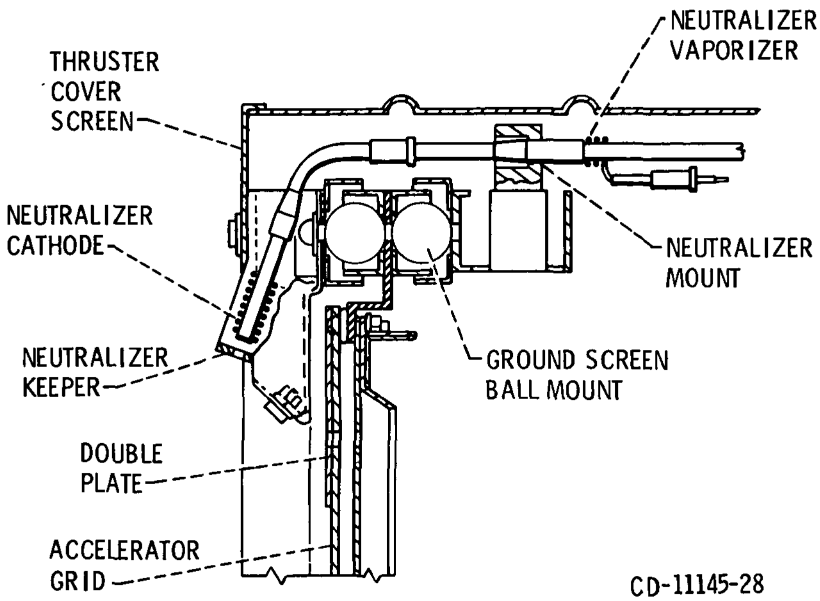

Figure 2. - Cross-sectional view of neutralizer assembly.

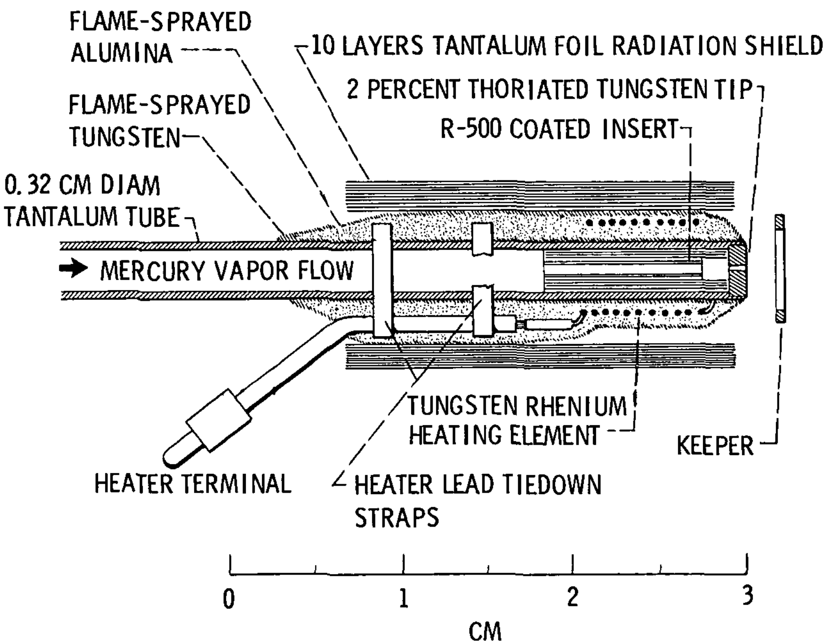

Figure 3. - Details of cathode heater and insert.

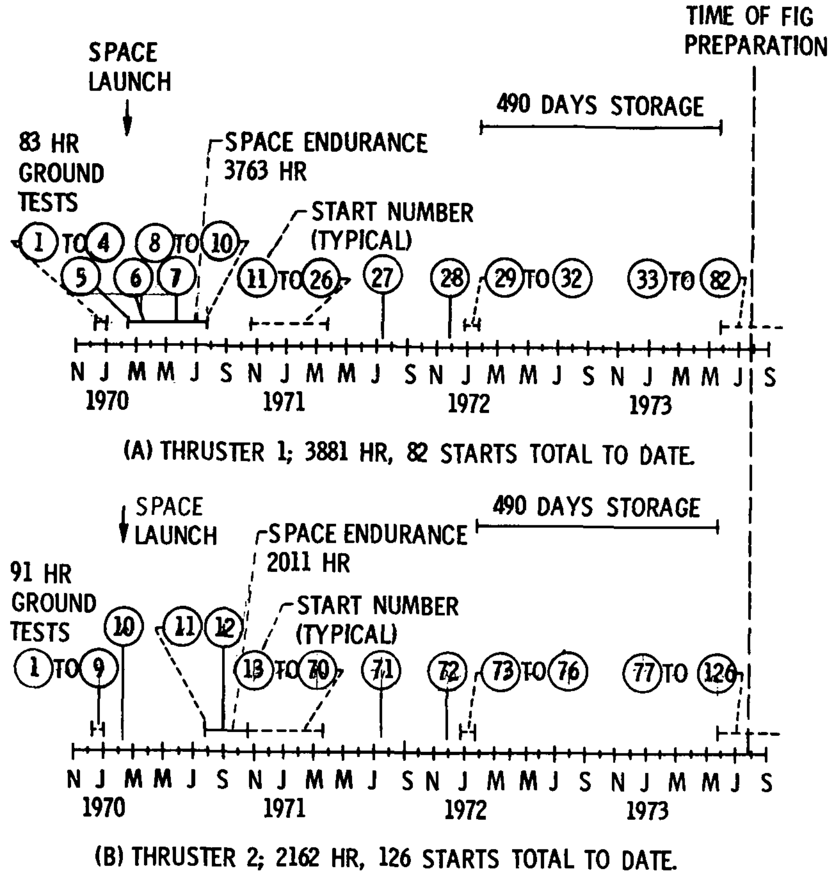

Figure 4. - Chronological representation of SERT II thruster preheats (starts), endurance running, and storage periods.

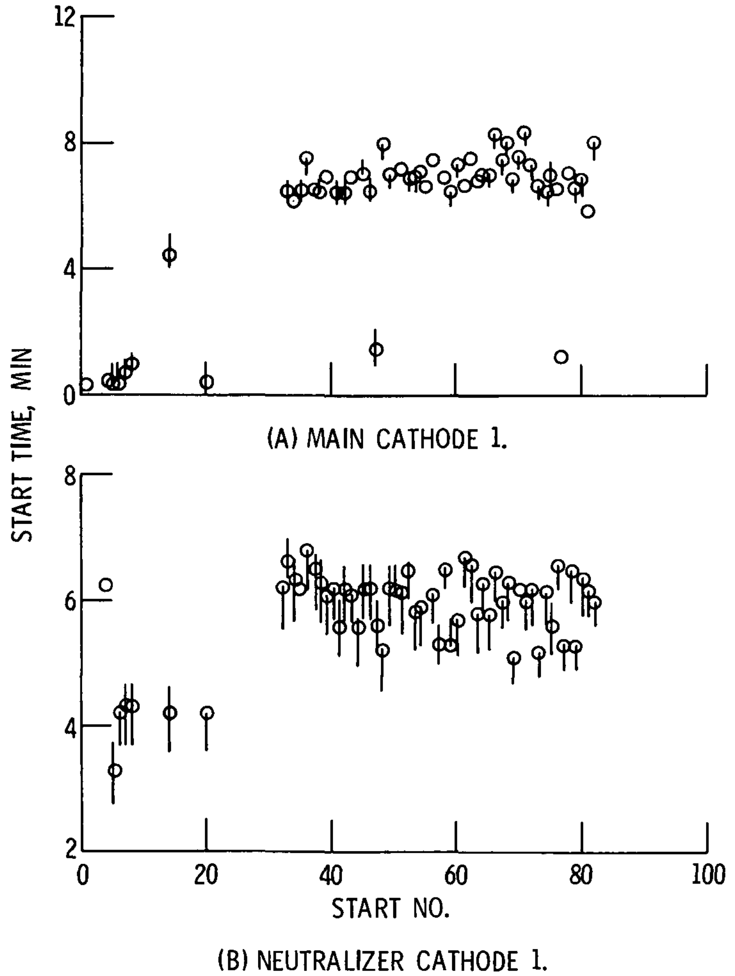

Figure 5. - Thruster 1; variation of cathode starting time. (Vertical bars represent telemetry data uncertainty time.)

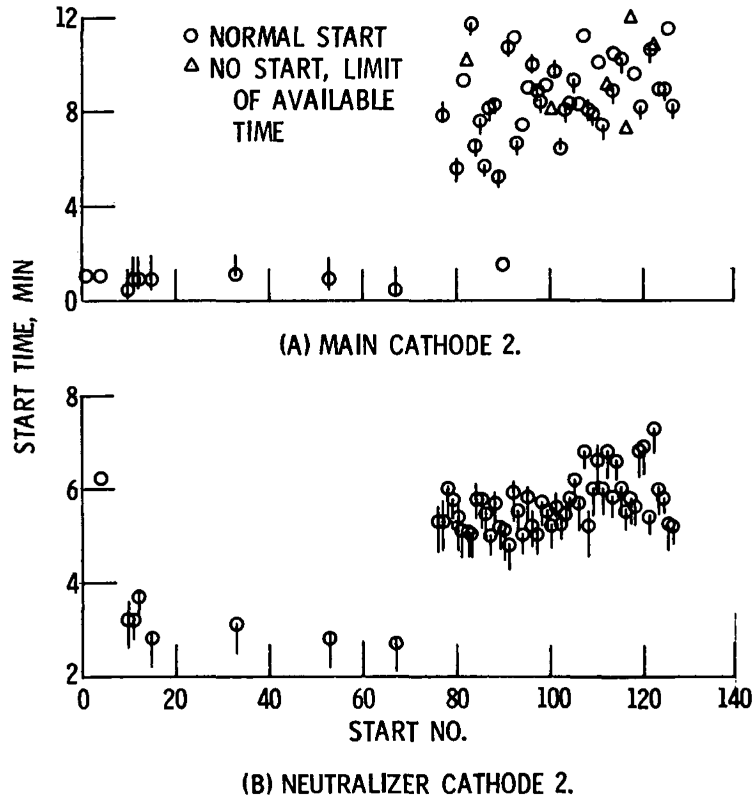

Figure 6. - Thruster 2; variation of cathode starting time. (Vertical bars represent telemetry data uncertainty time.)

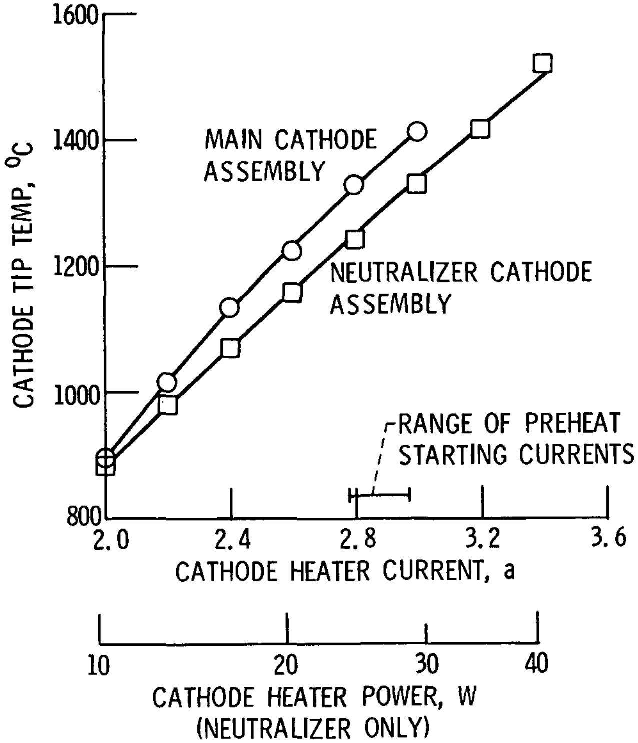

Figure 7. - SERT II cathode equilibrium temperature, no discharge. (Temperature corrected for surface emissivity and window loss.)

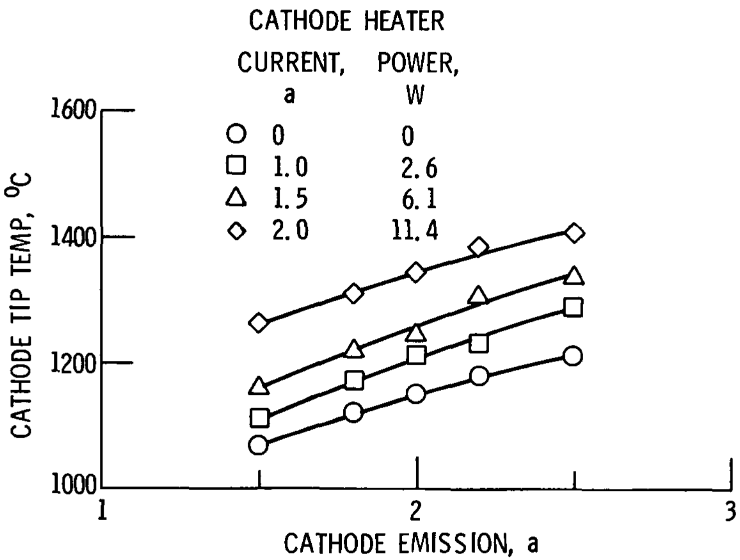

Figure 8. - SERT II main cathode tip temperature in thruster, no beam extracted. Total propellant, 0.30 a; anode, 30 to 32 V; keeper, 0.3 a at 4 to 10 V. (Temperature corrected for surface emissivity and window loss.)